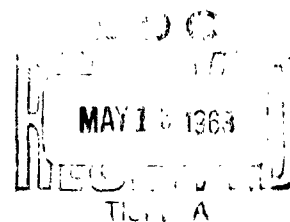63-3-3

403 346

Nonr - 3608(00)

Special Report

HEAT OF FORMATION OF
LiAlH$_4$

National Research Corporation

FOR ERRATA

AD **403346**

THE FOLLOWING PAGES ARE CHANGES

TO BASIC DOCUMENT

ERRATA SHEET

Pertaining   to

Special   Report

"HEAT OF FORMATION OF LITHIUM ALUMINUM HYDRIDE"

April 26, 1963   Nonr-3608(00)

In this work, a correction for the presence of $LiAlO_2$ in

the $LiAlH_4$ was required. It was necessary to know its heat of

reaction with HCl. This was calculated from heats of formation

data of the products and reactants. In so doing, the value for

the heat of formation of $LiAlO_2$ was obtained from Kubaschewski

and Evans, "Metallurgical Thermochemistry", as -12.9 kcal/mole.

The heat of reaction obtained from this calculation was reported

(last line, page 4) as -319.5 kcal/mole. A check of this

calculation shows that the heat of formation value given by

Kubaschewski was from the oxides, and, as such should not have

been used in my calculation. The correct value of the heat of

formation of $LiAlO_2$ from the elements, can be calculated to be

-284 kcal/mole. Using this value in the calculation to determine

the heat of reaction of $LiAlO_2$ with HCl, we arrive at -49.4 kcal/mole.

Since an experimentally measured value exists(of which we were not

aware at the time of the writing), this value should be used in

preference to the calculated value. The measured value is that

of J. P. Coughlin, J. Am. Chem. Soc. 79, 2397 (1957) and reported

to be -46 kcal/mole.

On the basis of the above, the following changes should be made:

Page	Line	Reads	Change to
5	5	-2.240	-0.339 kcal
5	7	-2.313	-0.412
5	8	-163.640	-165.541
5	9	-168.558	-170.520
5	16	-168.56	-170.52
5	20	-26.63	-24.67
6	17	-168.56	-170.52
6	23	-26.63	-24.67
ii	8	-163.56	-170.52
ii	11	-26.63	-24.67
ii	12	1)%	omit

The heat of formation of $LiAlF_4$ determined in this laboratory is therefore corrected from -26.63 to -24.67 kcal/mole.

Research Division

NATIONAL RESEARCH CORPORATION

70 Memorial Drive

Cambridge 42, Massachusetts

NRC Project 54-1-0226

Nonr - 3608(00)

Special Report

HEAT OF FORMATION OF
LiAlH$_4$

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26 April 1963

TABLE OF CONTENTS

ABSTRACT

The heat of formation of lithium aluminum hydride ($LiAlH_4$) has been determined by measuring the heats of solution of aluminum, lithium, and lithium aluminum hydride in 4N HCl. The heats of solution were found to be:

$$\triangle H_{298}°, \text{ kcal/mole}$$

Al	=	-128.14 ± 0.39
Li	=	$- 67.05 \pm 0.53$
$LiAlH_4$	=	-168.56 ± 1.31

From this data, the heat of formation of lithium aluminum hydride was calculated to be:

$$\triangle Hf° \text{ at } 25°C = -26.63 \pm 0.31 \text{ kcal/mole}$$

This value differs by 11% from the value of -24.08 ± 0.35 kcal/mole as determined by Davis, et al,[1] which is the value presented in Circular 500 NBS. This latter value was the only one found by a search of the literature. The value determined in this work alters any chemical propulsion calculation utilizing this information.

I INTRODUCTION

Accurate calculations in chemical thermodynamics depend upon the existence of reliable thermochemical information. It is often found that the available data is scarce and/or uncertain. A literature search has shown that the only reported value for the heat of formation of $LiAlH_4$ was determined by W. D. Davis, et al,[1] and found to be -24.08 ± 0.35 kcal/mole.

In that work the heat of reaction of the hydride with $HCl.50 H_2O$ was measured. By applying the known heats of formation of the other reactants and products, the heat of formation of the hydride was calculated.

The work reported here describes the experimental determination of the heat of formation of $LiAlH_4$ by separately measuring the heat of solution of aluminum, lithium, and lithium aluminum hydride in 4N HCl. From this heat of solution data, the heat of formation of the hydride was obtained by applying Hess' Law of Constant Heat Summation.

II APPARATUS

The calorimeter is described in detail in Appendix I. It consists essentially of an adiabatically operated, Parr combustion calorimeter, modified to increase its sensitivity. The temperature sensing element is a thermistor in a Wheatstone bridge network with a sensitivity of 6.8×10^{-5} °C or 0.17 calories. Under adiabatic conditions the thermal leak rate is 7×10^{-5} deg. min^{-1}. The reaction was carried out in a bomb in which the liberated hydrogen was confined.

III CALIBRATION

Appendix II gives the details of the apparatus calibrations.
The system was calibrated electrically by the standard procedures.
A chemical check was made by measuring the heat of reaction of
magnesium. As shown in the appendix, favorable agreement is found
with existing data for the material.

IV MATERIALS

The following materials were used in this work:

Material	Source	Purity
Aluminum	Mallinkrodt Chemicals	99.9 %+
Lithium	Lithium Corporation of America	99.9 %+
Magnesium	New England Lime Company	99.9 %+
$LiAlH_4$	Metals Hydride, Incorporated	97.08%+

The analysis of the above data is presented in Appendix III.
The analysis of the $LiAlH_4$ shows:

	% by weight
$LiAlH_4$	97.08
LiCl	.92
$LiAlO_2$	1.22
inert	.78

V EXPERIMENTAL

One-hundred fifty ml. of 4N HCl was added to the bomb. To
this (for the aluminum and lithium aluminum runs) was added 4
drops (0.17 gm) of 10% platinum chloride solution as a catalyst
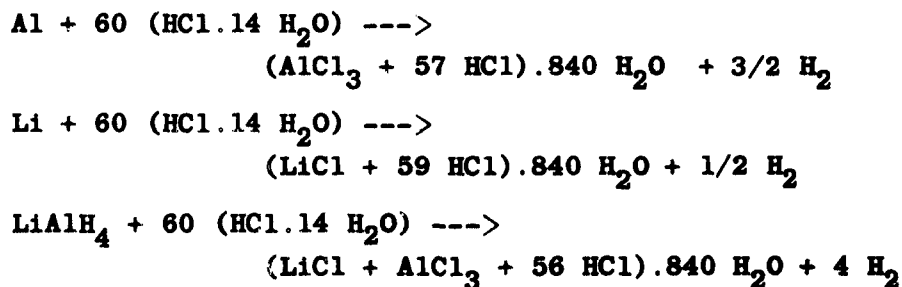to hasten the reaction rates. It was found that without the use

of the catalyst for the hydride runs, the final phases of dissolution were too slow. The rate of dissolution of aluminum was increased many-fold.

The samples were sealed under argon in glass ampoules. A dry box was used for preliminary preparation of the lithium and the lithium aluminum hydride. The sample-containing ampoule was placed in the bomb, the lid put in place, and the air exhausted from the bomb. Argon was allowed to replace the air. This procedure prevented the possible ignition of the hydrogen-oxygen mixture which would be present during and after a run. The omission of this step resulted in an H_2-O_2 combustion in an early run.

The bomb was placed in the calorimeter bucket and 2000 ml of distilled water added. The bucket and jacket temperatures were adjusted to 24.85 to 24.86°C. Upon reaching equilibrium conditions the reaction was initiated by turning down the central shaft which lowered the baffle plates and crushed the glass ampoule. All runs were performed adiabatically. The evolved hydrogen was confined within the bomb during each of the runs.

VI RESULTS

From the amounts of materials used, the following equations represent the reactions studied:

$$Al + 60 \ (HCl.14 \ H_2O) \longrightarrow$$
$$(AlCl_3 + 57 \ HCl).840 \ H_2O + 3/2 \ H_2$$

$$Li + 60 \ (HCl.14 \ H_2O) \longrightarrow$$
$$(LiCl + 59 \ HCl).840 \ H_2O + 1/2 \ H_2$$

$$LiAlH_4 + 60 \ (HCl.14 \ H_2O) \longrightarrow$$
$$(LiCl + AlCl_3 + 56 \ HCl).840 \ H_2O + 4 \ H_2$$

Heats of reaction at constant volume, $\triangle$ E, were converted to their corresponding constant pressure values by the equation:

$$\triangle \text{ H } = \triangle \text{ E } + \triangle \text{ n RT}$$

Tables II and III present the experimental data and calculations. Run Li-9 shows no measureable effect by doubling the sample weight. Runs Al-10 and Al-11 were made in 4N HCl containing lithium ions at a concentration equal to that following a lithium run. No significant difference is noted when compared with aluminum runs made in the absence of the lithium ions. The possibility of interaction at these dilutions is shown to be negligible.

Since the only data available on the heat of solution of lithium aluminum hydride was done in 1N HCl, a separate run was made at this dilution (Run $LiAlH_4$-17). No significant difference was detected when compared with other hydride runs in 4N HCl. A comparison of the data is, therefore, possible.

A correction for the catalyst used was made as follows:

$$H_2P_tCl_6 \text{ (soln) } + 2H_2(g) \text{ ---> Pt(c) } + 6HCl \text{ (soln)}$$
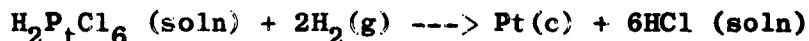
where: $\triangle H_{298} = -72.8$ kcal/mole

The correction for the amount used was +2.5 cal. The total heat evolved for those runs in which the catalyst was employed was 1200 to 1800 calories.

Corrections for the impurities in the $LiAlH_4$ are based on the following equations:

	kcal/mole
LiCl(c) ---> LiCl in 800 H_2O	- 8.8
$LiAlO_2$ + 4HCl(aq) --->	-319.5
LiCl + $AlCl_3$ + 2 H_2O	
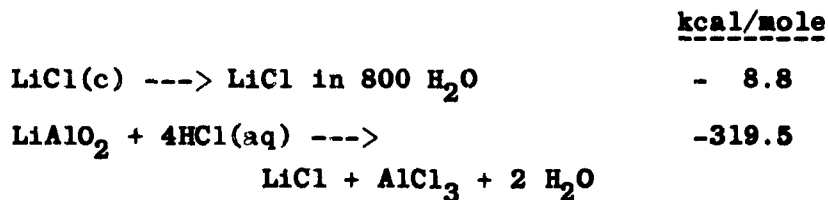
$\triangle$ H [1] was obtained from Circular 500[7]. $\triangle$ H [2] was calculated from heats of formation data obtained from the same source. The actual corrections for the impurities are as follows:

$LiCl$ = -.073 kcal

$LiAlO_2$ = -2.240 kcal

$LiAlH_4$ purity = 97.08%

i.e. $\triangle$ H_{298} ($LiAlH_4$) = -165.953 - (-2.313)

= -163.640 kcal/mole 97.08% $LiAlH_4$

= -168.558 kcal/mole $LiAlH_4$

Calculation of heat of formation of $LiAlH_4$:

	kcal/mole
$Al + 3HCl$ (aq) ---> $AlCl_3 + 3/2\ H_2$	-128.14 $\pm$ 0.31% or 0.397 kcal
$Li + HCl$ (aq) ---> $LiCl + 1/2\ H_2$	-67.05 $\pm$ 0.79% or 0.529 kcal
$LiAlH_4 + 4HCl$ (aq) ---> $LiCl + AlCl_3 + 4\ H_2$	-168.56 $\pm$ 0.78% or 1.31 kcal

---

$Li + Al + 2\ H_2$ ----> $LiAlH_4$

$\triangle$ Hf_{298} = $\triangle$ H_1 + $\triangle$ H_2 - $\triangle$ H_3

= -26.63 kcal/mole $\pm$ 1.15% or 0.31 kcal

VII DISCUSSION

A comparison of this data with existing data is presented below:

$Al + 3HCl$ (aq) ---> $AlCl_3 + 3/2\ H_2$
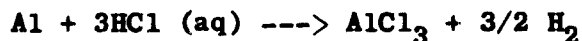
Investigator	Year	$\triangle H_{298}$	Comment
Richards, et al[8]	1910	-126.0	H_2 liberated
Biltz, et al[9]	1922	-125.1	---
Young[10]	1944	-126.8	H_2 liberated
Messer[11]	1960	-127.5	H_2 liberated
Circular 500 NBS[*]	1952	-128.5	---
This work	1963	-128.1	H_2 confined

No data of the heat of reaction of lithium with aqueous HCl has been found. The value of -66.5 kcal/mole has been obtained by calculation[12,13]. This work reports -67.05 kcal/mole as determined directly. Calculation based on Circular 500 data yields -67.44 kcal/mole.

The heat of reaction of $LiAlH_4$ in 1N HCl has been reported by Davis, et al[1]. The value for $\triangle H_{298}$ in 1N HCl is given as -165.87 kcal/mole by the investigators. The material used is reported as 99.05% $LiAlH_4$. The value determined in this work, corrected for impurities is -168.56 kcal/mole.

For comparison of the value for the heat of formation of $LiAlH_4$ the Davis paper remains the only source. In that work, the heat of reaction of $LiAlH_4$ with 1N HCl was measured. By applying existing values of the heats of formation of the other reactants and products, the heat of formation of $LiAlH_4$ was calculated to be -24.08 kcal/mole. The value determined in this work is -26.63 kcal/mole.

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[*]Calculated from data given in Circular 500

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APPENDIX I

APPARATUS

The heats of solution were measured in a modified Parr combustion calorimeter operated adiabatically (see Figure I). The bomb (see Figure II) consisted of a nickel alloy body, the inner wall of which was gold-plated. A special lid was constructed through which passed a centered, gas-tight, moveable shaft. Two baffle plates were attached to the bottom section of the shaft which allowed the sample (contained in a glass vial) to be crushed while submerged in the acid. The plates further prevented splattering resulting from violent reactions. A thin tantalum sheet was placed on the bottom of the bomb. The bottom plate was constructed of tantalum, also. The lid bottom, shaft, and upper baffle were also gold-plated for protection against attack by the acid. A relief value was also built into the lid to exhaust the bomb prior to a run and to release hydrogen following the run.

The lid to the calorimeter jacket was modified to allow the crushing shaft, thermistor tube, and heater tube to pass through to the calorimeter bucket contained within. Beckmann thermometers were used to monitor the bucket and jacket water temperatures. Improvements in water circulation were made by increasing the rate of stirring (small pulley used) and by placing a tube around the stirrer blades.

APPENDIX II

CALIBRATIONS

Temperature measurements were made by employing a GB32P8 Fenwal thermistor of 2 kilohms in one arm of a Wheatstone bridge network and powered by one mercury battery of 1.35 volts. The bridge is kept balanced by manipulating three 10-step decades totaling 111 ohms located in a second arm of the bridge. The output is amplified utilizing a Leeds and Northrup microvolt amplifier 9835-A (see Figure IV).

The sensitivity of the system is 6.8×10^{-5} °C per 0.5 division on the amplifier meter. Operating under adiabatic conditions the thermal leak rate was approximately 7×10^{-5} deg. min^{-1}.

The heater by which the calorimeter was electrically calibrated consisted of 15 inches of Cupron wire non-inductively wound on a threaded nylon plug and immersed in mineral oil contained in a glass well. The total resistance of the heater was 23.96 ohms as determined from voltage drop measurements. Energy from the heater is supplied by a 12 volt storage battery. The timing of the heater was measured by a Model S-10 Standard precision timer synchronized with the heater switch. The heater circuit is shown in Figure III.

The reactions studied create temperature increases of 0.2, 0.4, and 0.6 deg. C. Electrical calibrations were made accordingly, because of the characteristic non-linearity of the temperature coefficient of resistance of the thermistor. The heater current was measured by the potential drop across an 0.5 ohm standard wire-wound resistor, utilizing a K-2 potentiometer.

All experimental runs, including calibrations were initiated

at a temperature between 24.85 and 24.86°C. The three ranges of thermistor resistance corresponding to temperature changes of approximately 0.2, 0.4, and 0.6°C are 18, 36, and 54 ohms respectively. The heat input was calculated as follows:

$$q, \text{cal} = .2389 \left(\frac{E_s}{R_s}\right)^2 R_h (t_{sec}) \qquad \text{where:}$$

E_s — voltage drop across standard resistor

R_s — 0.500 Ω standard wire-wound resistor

R_h — heater resistance = 23.96 Ω

t_{sec} — heating time

The results of the electrical calibration runs are shown in Table I. The uncertainties listed throughout this work are twice the standard deviation in accordance with Rossini[2].

In addition to the electrical calibrations, a chemical check of the apparatus was made by measuring the heat of reaction of magnesium with 1N HCl. (see Table II)

The use of 1N HCl for the magnesium runs necessitated separate energy equivalent determination since the acid concentration differed from that used in the remainder of the study. (see Table I)

The heat of reaction of magnesium with 1N HCl was found to be -111.73 $\pm$ 0.56 kcal/mole. A favorable comparison was made with other available data in which the 1N HCl solvent was used.

Investigator	Result $\pm$ 2σ kcal/mole
Shomate and Huffman[3]	-111.3 $\pm$ 0.02
Lohr[4]	-111.3 $\pm$ 2.4
Westman[5]	-111.2

Investigator	Results $\pm$ 20 kcal/mole
Argue[6]	-111.2 $\pm$ 0.25
This work	-111.7 $\pm$ 0.56

It is to be noted that in the work of this author the evolved hydrogen was confined within the bomb, whereas in the work of the others reported above, the hydrogen was allowed to escape, with corrections made accordingly.

APPENDIX III

MATERIALS

Lithium --

The lithium metal was obtained from Lithium Corporation of America as 99.9% lithium.

Spectrographic Analysis of Lithium

Element sought	Found (ppm)
Fe	1
Ni	<1
Cr	<1
Al	<10
Ti	ND<1
Cu	<5
Ca	10
Mg	10
V	ND<1
Pb	ND<5
Sn	ND<1
Mn	<1
Co	ND<10

Aluminum --

The aluminum wire was obtained from Mallinkrodt Chemicals.

Element sought	Found (ppm)
Ni	0<10
Ti	0<10
Fe	10
Cr	<10
Mg	<10
Mn	ND<5
Si	10
B	ND<10
V	ND<10
Cu	<10

Magnesium --

The magnesium metal was obtained from New England Lime Company.

Spectrographic Analysis of Magnesium

Element sought	Found (ppm)
Al	ND<10
Ca	<10
Sn	5
V	ND<10
Cu	10
Pb	100
Mn	80
B	100
Cr	ND<10
Ni	<10
Fe	80

Lithium Aluminum Hydride --

The lithium aluminum hydride was purchased from Metals Hydride Incorporated. The material was subjected to chemical analysis and yielded the following results:

Spectrographic Analysis of $LiAlH_4$

Element sought	Found (ppm)
Fe	<0.05
Cr	ND<0.05
Ni	ND<0.05
Si	0.05
Mg	<0.005
Pb	ND<0.05
Sn	0.03
Ca	ND<0.05
Cu	<0.03
Na	ND<0.5
B	ND<0.05

Lithium in lithium aluminum hydride --

The lithium content was found by the flame photometric method[a]
to be: 17.70%
                                17.71%   = 17.71% by weight (average)

Aluminum in $LiAlH_4$ --

The aluminum content was found by the EDTA[b] method to be:

                                69.64%
                                69.56%
                                69.24%   = 69.45% by weight (average)
                                69.37%

Hydrogen evolution --

Analysis of the sample by reaction with 10% H_2O in dioxane
mixture yielded the following:

                                10.31% H_2
                                10.30% H_2
                                10.34% H_2 = 10.32% H_2 by weight
                                10.32% H_2

X-ray diffraction pattern indicated no impurity phases.

Gravimetric chlorine analysis showed 0.77% Cl. Assuming this
to be in the form of LiCl, this would yield 0.92% LiCl in sample.

On the basis of the hydrogen evolution data, the material is
97.08% $LiAlH_4$. By calculation, this material should contain 17.76%
lithium and 68.95% aluminum. As stated above 17.71% lithium and
69.45% aluminum were found. It was assumed that the difference
between the calculated and found aluminum was in the form of $LiAlO_2$,
a compound which would result from the pick-up of moisture. This
would result in 1.22% $LiAlO_2$.

The additional lithium resulting from the LiCl and $LiAlO_2$
----
[a]The uncertainty of the method at $\pm 2\sigma$ = 0.38%
[b]The uncertainty of the method at $\pm 2\sigma$ = 0.14%

would increase the calculated lithium content by 0.27% resulting
in a total lithium of 18.03%. The lithium found was 17.71%
$\pm$ 2σ = $\pm$ 0.38, indicating the upper limit at 18.09% below which
the total calculated lithium lies.

The above analytical study indicates the material to be:

$LiAlH_4$	97.08%
LiCl	.92
$LiAlO_2$	1.22
inert	.78
	100.0%

TABLE I

ELECTRICAL CALIBRATIONS

Run No.	q, cal	$\triangle$ R, Ω	$E = q/\triangle R$, cal/Ω
C-Al-14	1151.8	31.884	-36.12
C-Al-15	1154.1	32.088	-35.97
C-Al-27	1278.7	35.652	-35.87
C-Al-28	1336.3	37.041	-36.08
C-Al-29	1068.8	29.700	-35.99
C-Al-30	1295.6	35.856	-36.13
Mean			-36.03
Uncertainty			0.08
%			0.22
C-Li-16	669.0	18.597	-35.97
C-Li-17	676.9	18.856	-35.90
C-Li-18	743.3	20.657	-35.98
C-Li-19	758.5	21.038	-36.05
C-Li-20	663.9	18.462	-35.96
Mean			-35.97
Uncertainty			0.06
%			0.17
C-LiAlH$_4$-21	1847.2	51.020	-36.21
C-LiAlH$_4$-22	1661.5	45.957	-36.15
C-LiAlH$_4$-23	1598.8	43.824	-36.48
C-LiAlH$_4$-24	1864.2	51.285	-36.35
C-LiAlH$_4$-26	1737.8	48.009	-36.20
Mean			-36.28
Uncertainty			0.14
%			0.38
C-Mg-1	1088.06	30.043	-36.21
C-Mg-6	1081.85	29.970	-36.09
Mean			-36.15
Uncertainty			0.12
%			0.33

TABLE II

HEAT OF REACTION OF ALUMINUM WITH 4N HCl

Run No.	m, gm	$\triangle R, \Omega$	E, cal/Ω	E·$\triangle R$-c_{pt}*	-$\triangle E_{298}$ cal/mole	-$\triangle H_{298}$ cal/mole
Al-4	0.2404	31.909	36.03	1147.2	128757	127869
Al-5	0.2398	31.812	36.03	1143.7	128685	127797
Al-6	0.2696	36.010	36.03	1294.9	129593	128705
Al-7	0.2700	36.067	36.03	1297.0	129611	128723
Al-9	0.2701	35.971	36.03	1293.5	129213	128325
Al-10	0.2719	363.04	36.03	1305.5	129549	128661
Al-11	0.2707	36.034	36.03	1295.8	129.156	128268
Al-12	0.2703	36.111	36.03	1296.1	129377	128489

Mean 128230
Mean - C_{break} 12814.
Uncertainty 266
% 0.21

HEAT OF REACTION OF LITHIUM WITH 4N HCl

Run No.	m, gm	$\triangle R \Omega$	E, cal/Ω	E·$\triangle R$-c_{pt}	-$\triangle E_{298}$ cal/mole	-$\triangle H_{298}$ cal/mole
Li-1	0.0696	18.764	35.97	674.9**	67286	66990
Li-2	0.0777	20.935	35.97	753.0**	67247	66951
Li-3	0.0768	20.758	35.97	746.7**	67465	67169
Li-7	0.0835	22.911	35.97	824.1**	68484	68188
Li-8	0.0954	25.446	35.97	915.3**	66575	66279
Li-9	0.1395	37.701	36.03	1358.4**	67569	67273

Mean 67142
Mean - C_{break} 67052
Uncertainty 516
% 0.77

*c_{pt} = Catalyst Correction = 2.5 cal/0.17 gm H_2PtCl_6 (10% solution)

TABLE III

HEAT OF REACTION OF LITHIUM ALUMINUM HYDRIDE IN 4N HCl

Run No.	m, gm	$\triangle R$, Ω	E, cal/Ω	E·$\triangle$R-C pt	$-\triangle E_{298}$ cal/mole	$-\triangle H_{298}$ cal/mole
LiAlH$_4$-6	0.4108	50.327	36.28	1823.4	168458	166089
LiAlH$_4$-7	0.4306	52.739	36.28	1910.9	168424	166055
LiAlH$_4$-9	0.3992	48.823	36.28	1768.8	168162	165793
LiAlH$_4$-10	0.3367	41.196	36.28	1492.1	168188	165819
LiAlH$_4$-12	0.3862	47.130	36.28	1707.4	167789	165420
LiAlH$_4$-14	0.3312	40.957	36.28	1480.9	169697	167328
LiAlH$_4$-15	0.3369	41.359	36.28	1495.5	168471	166102
LiAlH$_4$-16	0.3471	42.498	36.28	1536.8	168036	165667
LiAlH$_4$-17*	0.3799	46.241	36.58	1686.5	168483	166114
Mean						166043
Mean - C***break						165953
Uncertainty						113
%						0.68

HEAT OF REACTION OF MAGNESIUM IN 1N HCl

Run No.	m, gm	$\triangle R$, Ω	E, cal/Ω	E·$\triangle$R-C pt	$-\triangle E_{298}$ cal/mole	$-\triangle H_{298}$ cal/mole
Mg-1	0.2400	30.627	36.15	1107.2**	112159	111567
Mg-2	0.2405	30.700	36.15	1107.3	111936	111344
Mg-3	0.2404	30.899	36.15	1117.0**	112964	112372
Mg-6	0.2404	30.930	36.15	1113.1	112569	111977
Mean						111815
Mean - C break						111725
Uncertainty						454
%						0.41

*1N HCl as solvent
**No catalyst used
***Correction for breaking sample
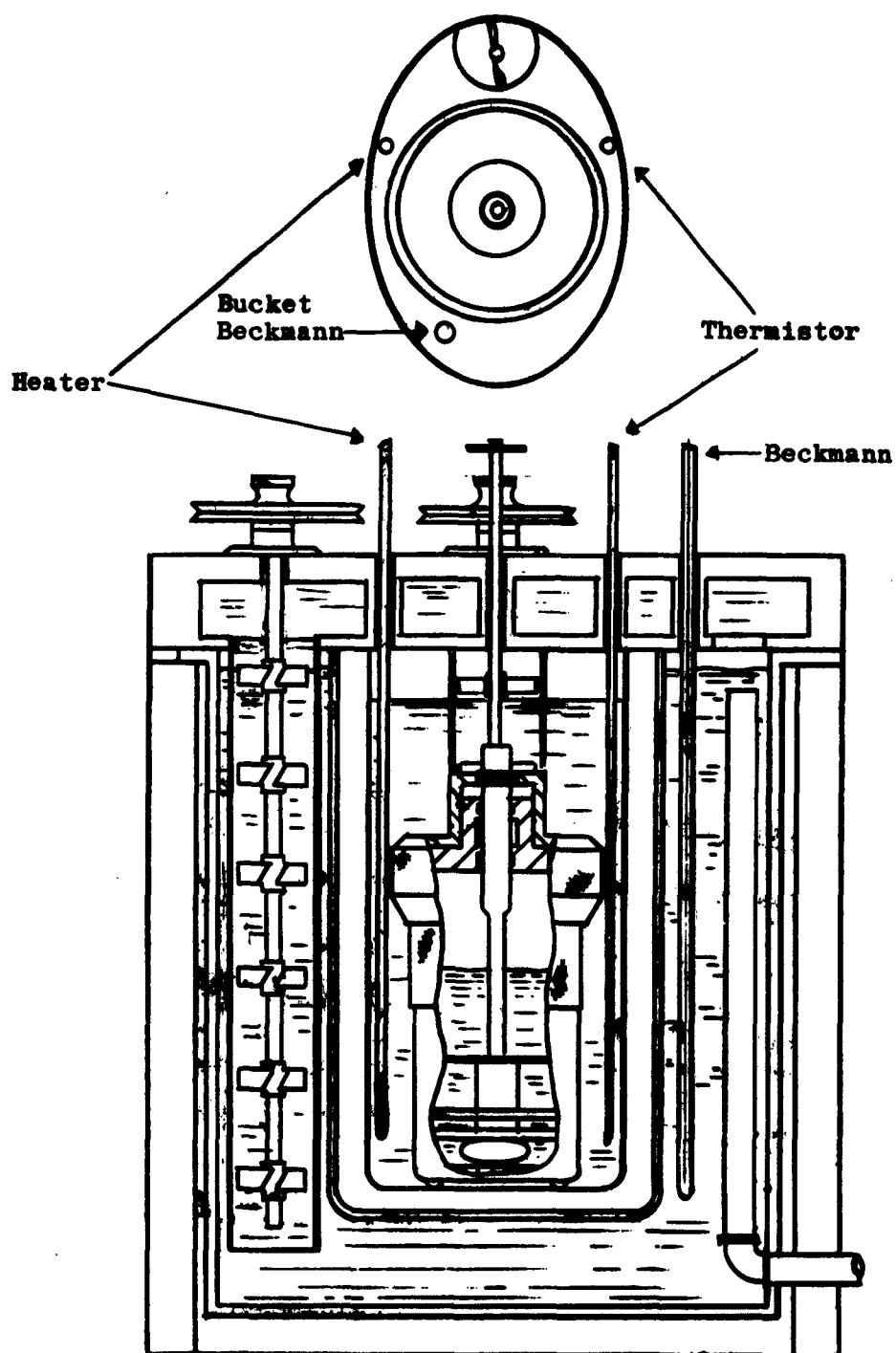
FIGURE I

FIGURE II

REACTION BOMB

Pressure Release

Grease Packing

"O" Ring

Acid Level

Tantalum
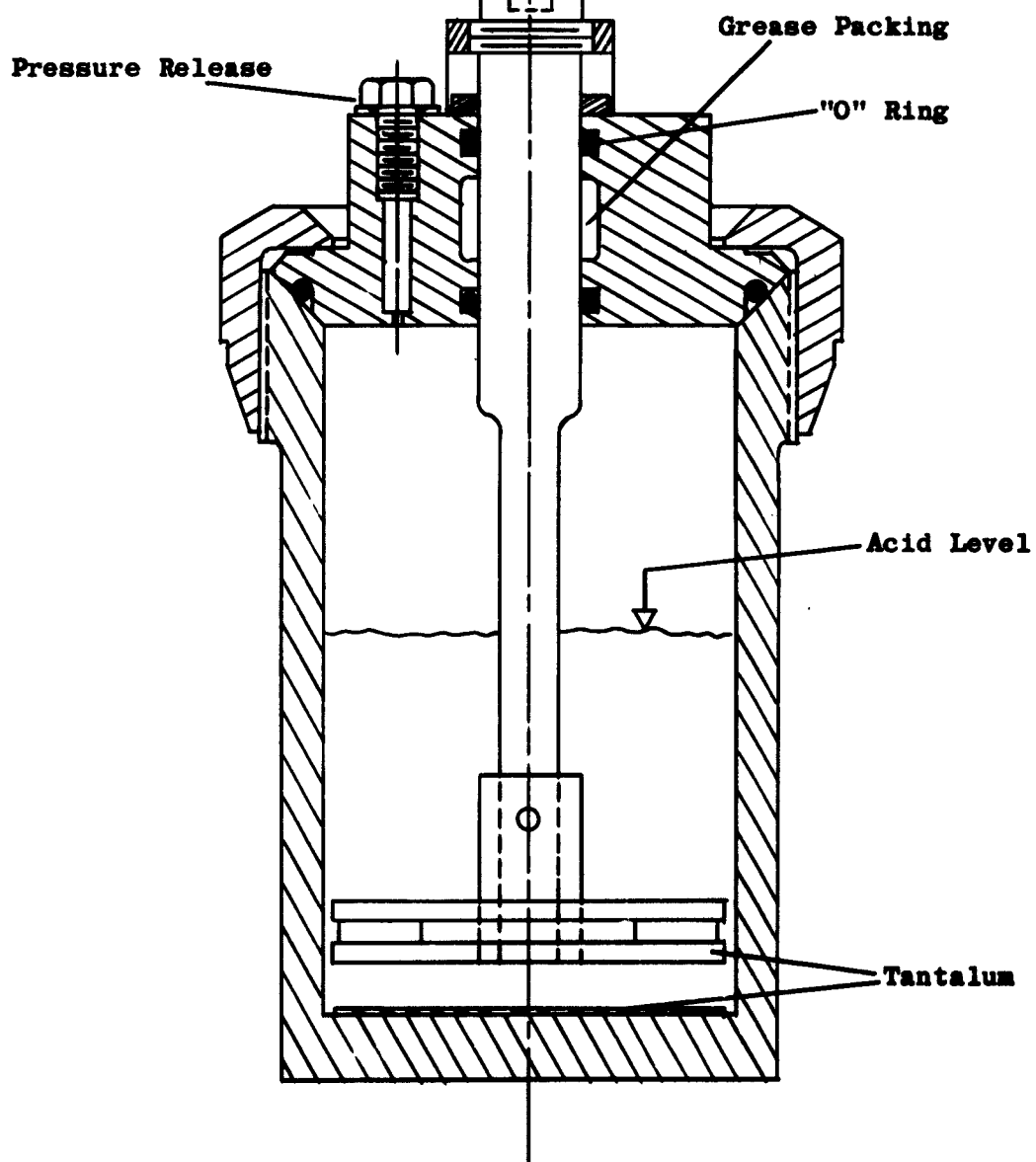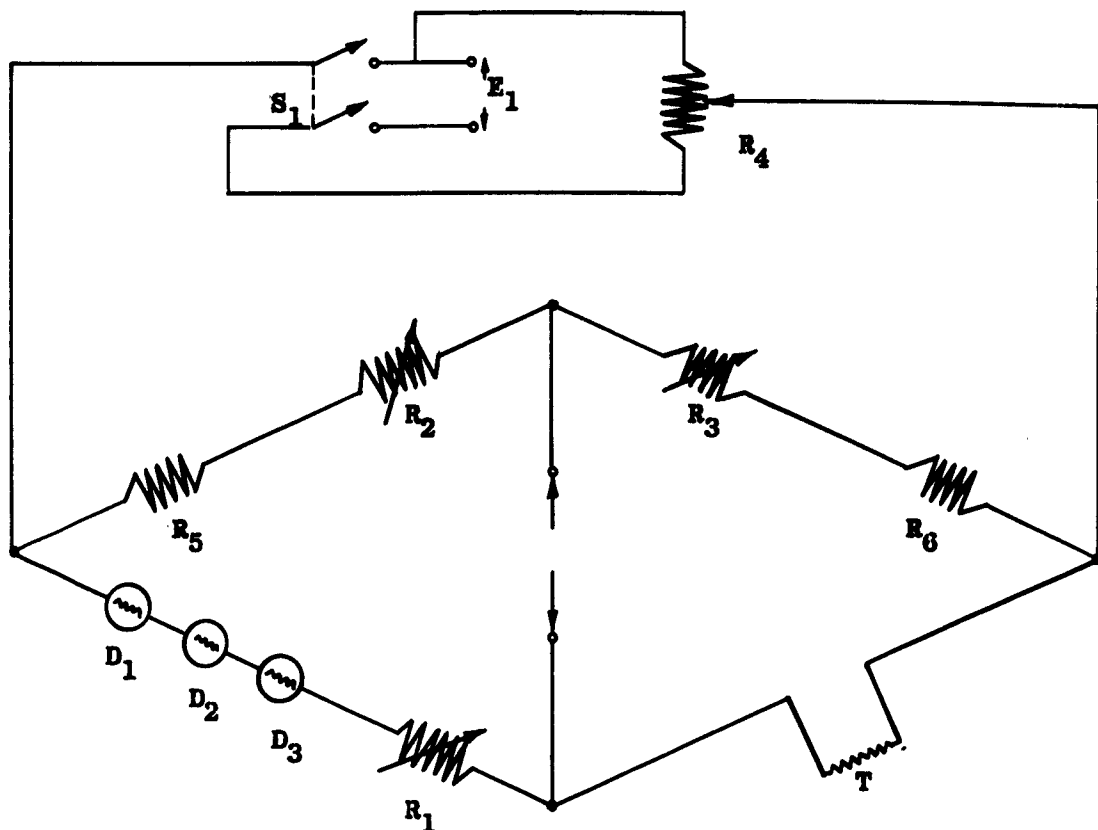
HEATER CIRCUIT
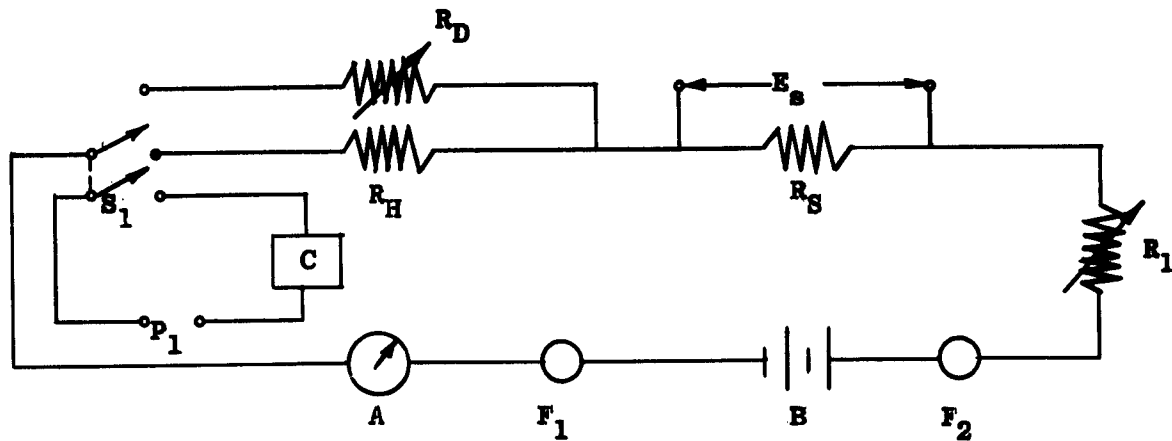
S_1 - DPDT L&N switch

C   - Precision timer

A   - 0-5 amp ammeter

F_1, F_2 - 3 amp fuses

B   - 12 volt lead storage battery

R_1 - Rheostat (72 ohm, 3.1 amp)

E_s - Receptacle for voltage drop measurement

R_s - 0.5 ohm (2 watt) Shallcross resistor

R_H - heater (Cupron wire)

R_D - dummy heater

P_1 - 110 volt H.C. receptacle

FIGURE III

THERMISTOR BRIDGE

R$_1$,R$_2$,R$_3$ - 2000 Ohm ten turn helipots

R$_4$ - 250 ohm ten turn helipots

R$_5$,R$_6$ - 100 ohm resistors

D$_1$ - .1 x 10 ohm resistance decade

D$_2$ - 1 x 10 ohm resistance decade

D$_3$ - 10 x 10 ohm resistance decade

S$_1$ - Single pole single throw toggle switch

E$_1$ - Mallory mercury battery (1.35 volts)

P$_1$ - Output to amplifier

T   - Fenwal thermistor GB32P8

FIGURE IV